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WOOD AND OTHER RENEWABLE RESOURCES

Environmental assessment and improvement alternatives of a ventilated wooden wall from LCA and DfE perspective

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Abstract
Purpose The main goal of this paper was to analyse the environmental profile of a structural component of a wooden house: a ventilated wooden wall, by combining two environmental methodologies: one quantitative, the life cycle assessment (LCA) and another qualitative, the design for the environment (DfE).
Methods The LCA study covers the whole life cycle of the ventilated wall manufacture as well as its distribution, installation and maintenance. To carry out this analysis, a Galician wood company was assessed in detail, dividing the process into four stages: the assembling stage, the packing stage, the distribution to clients as well as the final installation and maintenance of the wooden wall.

Ten impact categories have been assessed in detail in the LCA study: abiotic depletion (AD), acidification (AC), eutrophication (EP), global warming (GW), ozone layer depletion (OD), human toxicity (HT), fresh water aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME), terrestrial ecotoxicity (TE) and photochemical oxidant formation (PO).
Results and discussion According to the environmental results, the assembling stage was the most important contributor to the environmental profile with contributions from 57% to 87%, followed by the production of the electricity required. The detailed analysis of the assembling stage identified the most important environmental hot spots: the production of boards used in the structure [oriented strand board and medium density fibreboard (MDF)] as well as the transportation of the cedar sheets from Brazil.

Concerning the results of the DfE, a selection of different eco-design strategies was proposed from technological, economic and social points of view by an interdisciplinary team

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of researchers and company´s workers. The eco-design strategy considered the following improvement actions: (i) the substitution of the MDF in the wall structure; (ii) the use of German red pine sheets; (iii) the installation of solar panels in the facilities; (iv) the use of Euro 5 transport vehicles, (v) the use of biodiesel for transport; (vi) the definition of a maintenance protocol for the wooden materials; and (vii) the definition of a protocol for the separation of materials before disposal.

Conclusions The results obtained in this work allow predicting the influence of the selection and origin of the raw materials used on the environmental burdens associated with the process. Future work will focus on the manufacturing of a prototype of an eco-designed ventilated wooden wall.

Keywords Design for the environment (DfE) · Eco-design · Environmental assessment · Life cycle assessment (LCA) · Ventilated wooden wall · Wood sector

1 Introduction

Urban residents are increasing every year worldwide and this requires the construction of new urban infrastructures. The knowledge of the environmental profile of materials and processes used in the building sector has to be considered as a first stage to reduce their environmental impact as well as to introduce the final product into the ecological or green market (Azapagic et al. 2004; Oliver-Solá et al. 2009). Nowadays, buildings account for the largest share of the EU energy consumption (42%) and produce about 35% of all greenhouse gases emissions. For this reason, it is necessary to introduce sustainable solutions in the construction sector such as efficient heating installations, the use of renewable and/or recycled materials or the implementation of an efficient waste management scheme.

Life cycle assessment (LCA) methodology is a suitable and valuable tool to assess the environmental impact of materials, products and services, and should be part of the decision-making process towards sustainability (Baumann and Tillman 2004). Among the different materials that are largely used in the construction sector, wooden structures are one of the most relevant materials used for furniture, cabinets, flooring and mouldings.

Different LCA studies have been carried out for this type of wooden products:

- Boards: particleboards (Rivela et al. 2006), medium density fibreboards (MDFs; Rivela et al. 2007), hardboards (González-García et al. 2009a) and green hardboards (González-García et al. 2011a).
- Construction materials: floor coverings (Petersen and Solberg 2003; Nebel et al. 2006), window frames (Richter and Gugerli 1996; Asif et al. 2002) and walls (Werner 2001)
- Furniture (Taylor and van Langenberg 2003) and containers (González-García et al. 2011b)

Other wood-based products: paper pulp (González-García et al. 2009b, 2011c), writing paper (Lopes et al. 2003) and packaging materials (Farreny et al. 2008).

As far as wooden products are correctly installed and used, they tend to present a more favourable environmental profile than those of equivalent products from other materials (Werner and Richter 2007). However, several negative environmental consequences were identified in the production processes of boards such as the use of fossil-based synthetic resins (urea or phenol formaldehyde) as well as the limited recyclability of the final product (Imam et al. 1999; Bovea and Vidal 2004; Rivela et al. 2006, 2007; González-García et al. 2009a, 2011a). Nowadays, current research is being focused on the development of green adhesives where phenolic substances are to be substituted by lignosulfonates, lignin, tannin or starch-based materials (Moubarik et al. 2009; Widsten et al. 2009).

Not only LCA is the methodology to analyse and identify the environmental burdens associated to wooden products but also the named eco-design or design for the environment (DfE). This new methodology consists of applying environmental criteria to the development and design of a product and implies a change in how the consumers form an opinion about these products. This change in the design translates into a reduction of the environmental emissions and a consequent improvement of the environmental profile of the products under assessment (McDonough et al. 2003; Zust and Wirnmer 2004). Examples concerning the application of this methodology can be found in the automobile sector (Muñoz et al. 2006), the packaging and packing (Bovea and Gallardo 2006), the leather tanning industry (Rivela et al. 2004) and waste management (Todd et al. 2003).

The main goal of this paper is to analyse the manufacture process of the wooden wall as a representative product of the wooden construction sector by using the combined application of LCA and DfE as well as to compare its environmental profile with potential alternatives. Wooden houses represent one of the oldest construction styles in the world. This kind of houses is typical in Scandinavian countries, Russia and northern Europe. Moreover, Australia and South Africa built wooden houses from a lot of years ago. Nowadays, the construction method is based on the traditional one but including the new technological and industrial advances.

The wooden wall manufacture under study includes several types of materials such as wood sheets, rock wool, polyester

resins, gypsum-fibre sheets as well as plastic and metal pieces. Moreover, a specific treatment based on cupper salts is necessary for the wooden materials. The ventilated wooden wall is for outdoor uses; therefore, it requires a special maintenance based on the application of ecologic oil every 3 years. So far, no LCA and DfE studies are available for the production of wooden walls and houses.

2 Environmental assessment methods

2.1 Life cycle assessment

LCA has proved to be a valuable tool for analysing environmental considerations of a product (process and/or service) that need to be part of the decision making process towards sustainability. LCA allows the identification and implementation of opportunities to attain environmental improvements. The present study concerns the evaluation of a ventilated wooden wall production process from a ‘cradle to gate’ perspective, i.e. excluding the final disposal of the product from the analysis.

2.2 Design for the environment

DfE is a methodology which facilitates the communication of environmental factors to be taken into account in the design of a product (Smith and Wyatt 2006). Firstly, a multidisciplinary eco-design team has to be created to cover the fields of knowledge implied in DfE: environment and design. The interdisciplinary team in this study was made up of designers, engineers, environmental scientists, chemists and experts in the field of wood-based products. Secondly, the variables which define the product under assessment (implementation and complexity degree, representative materials) are described. The third step is the environmental assessment of the product by the application of LCA.

Once the results of the environmental impact associated to a product are obtained, the eco-*briefing* is carried out, which involves the proposal of the environmental objectives that would be considered in the eco-design process, such as the optimisation of the materials and energy used or the promotion of a better management scheme for the product waste (Gilbertson 2006). Alternatives that eco-briefing addresses with the aim of improving the current environmental conditions of the product are known as strategies of eco-design (Bhamra 2004; Ferrao and Amaral 2006).

The fifth step is based on the conceptual development of an eco-designed product and the last stage will consider the discussion of the eco-design alternatives as well as their environmental evaluation (including LCA analysis) in order to assess the degree of environmental improvement that is introduced by the eco-designed element.

3 The environmental assessment of a ventilated wooden wall

This paper aims to identify the environmental impacts associated with the production of a ventilated wooden wall as a wooden construction element. In this work, several objectives were proposed and two environmental methodologies were considered:

i) the LCA analysis to detect the environmental key factors of the ventilated wooden wall throughout its life cycle,
ii) the proposal of improvement alternatives for the most relevant impacts,
iii) the improvement of its environmental profile by means of the practical adaptation of the methodology of eco-design,
iv) the development of the eco-briefing concept as a communication tool to facilitate the understanding of environmental factors to designers and other company’s technicians not familiar with DfE.

A Spanish company located in Galicia (NW Spain), considered representative of the state-of-art, was selected to study the production process in detail. This company is one of the most important Spanish producers of wooden walls with more than 20 years of expertise dedicated to the construction of wooden houses with high quality, applying the most novel treatments and techniques. The assessment of this ventilated wall was carried out as this product has a good market share and presents similarities with other products manufactured in the factory; thus, the environmental solutions proposed for this product could be potentially applied to other products. Moreover, this is one of the most representative products of the company. The study considers the life cycle of the manufacturing process of the ventilated wooden wall from the production of raw materials to its delivery to the final user and maintenance.

3.1 Functional unit

The functional unit selected corresponds to a ventilated wooden wall (~169 kg) with a total area of 2.40 m^2 and a heat transfer coefficient of 0.37 $W\cdot m^{-1}\cdot K^{-1}$ (Helmer and Walker 2006). Figure 1 illustrates the characteristics of the structure under study. The product basically comprises a structure made up with boards [MDF and oriented strand board (OSB)] and wood (pine and Brazilian cedar). Moreover, rock wool, gypsum fibre and synthetic panels are used to reduce noise and avoid condensation as well as steel screws to join the different parts. The final product is varnished with beautification oil for its maintenance.

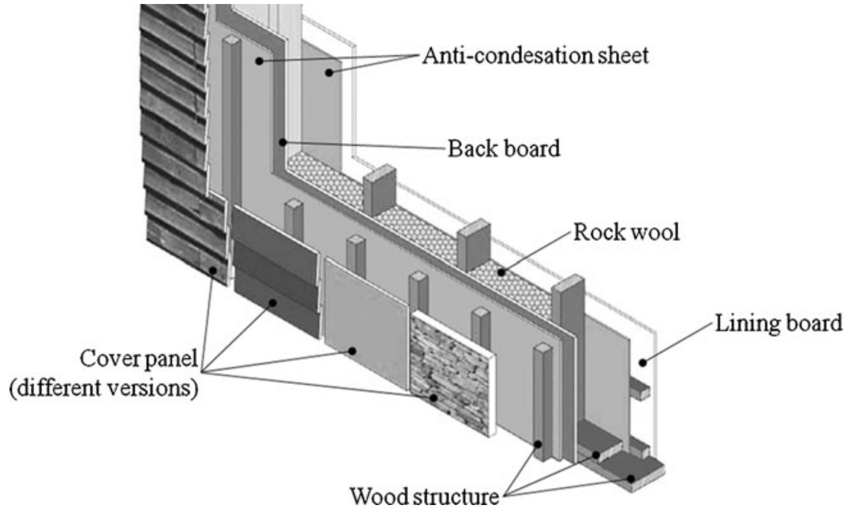


Fig. 1 Design of the ventilated wooden wall under assessment (~169 kg; 2.40 m^2)

3.2 Description of the system under study

The process chain was divided into four stages: the assembling stage, the packaging, the final distribution to clients and maintenance. Ancillary activities, such as electricity production, production and transport of chemicals, wooden boards and sheets, natural fibres, metal and plastic pieces or packaging materials, were also taken into account within the system boundaries. End-of-life treatment was not included in the system boundaries since this stage is out of reach of the company under assessment. The inventory data came from interviews, surveys and on-site measurements and were completed with bibliographic sources. The system assessed is illustrated in Fig. 2.

A mass balance analysis was performed for the production of the wooden wall. The production line consists on the production and reception of wood-based materials for the structure, metal pieces, such as screws and hoops, synthetic and natural fibres, and packaging materials (pallets, cardboards and plastics). After that, the wood-based boards and sheets are cut according to the dimensions of the wall structure, assembled and treated with copper salt. The next step is the packaging to be later distributed to the final user. Ventilated wooden wall is transported by truck and the average transport distance assumed in the study was 100 km. The construction of the house with the ventilated walls and their maintenance were included within the system boundaries. Concerning the maintenance, the average life for the wall is 45 years, and 0.262 kg of ecologic oil is required every 3 years.

Concerning the electricity requirements, they are directly taken from the Spanish national grid. Finally, wood wastes from the production process are mainly reused in the factory to manufacture other products. The excess of wood wastes is sent to a nearby wooden boards factory. The use of shaving and sawdust as fertilizer as well as the treatment of

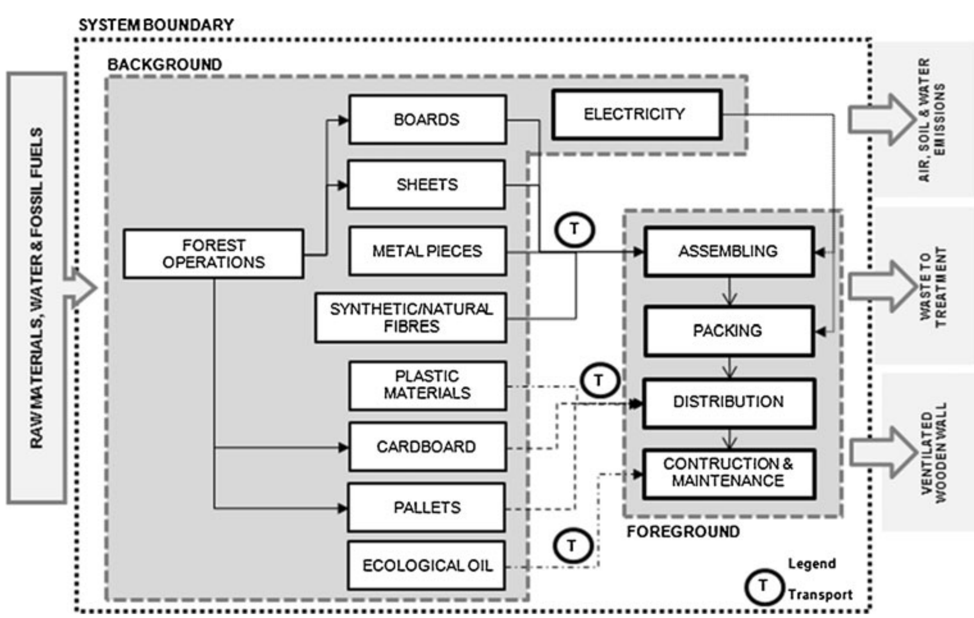


Fig. 2 System boundaries and process chain under study

remaining waste, such as plastics, pallets and cardboard for recycling, were not included in this study.

3.3 Data quality and simplifications

High-quality data is essential to make a reliable evaluation in an LCA analysis, and this step requires a lot of time and effort. Data for this study were collected from different sources. The inventory data for the foreground system consisted of average annual data obtained by on-site measurements in the company (Table 1).

Other inventory data for the background system, such as oil, metal pieces and packaging materials production, were obtained from databases (Table 2). Inventory data for the production of wood-based materials (boards and sheets) were taken from the Ecoinvent database (Werner et al. 2007). As it was mentioned before, all electricity requirements for the production process were taken from the Spanish national grid. Inventory data with regard to the production of electricity was taken from the Ecoinvent database (Dones et al. 2007).

Concerning waste generation, rejects from wood-based materials are reused in the own factory and the fraction in excess is sent to a nearby wooden boards factory. Other wastes from the packaging stage such as corrugated board, salt and oils are collected and sent to treatment. The treatment and distribution of these wastes were excluded from the system boundaries.

The inventory table of the global process is shown in Table 1, and extra data sources are summarised in Table 2.

3.4 Allocation procedure

Allocation is the partitioning of input or output flows of a process to the product under study and is one of the most critical issues in LCA studies when the production process involves more than one product. A feature of the furniture sector is the simultaneous production of diverse products; specifically in this company, not only the ventilated wall is produced but also other types of walls with different materials, dimensions and characteristics. Allocation was required in this study in order to allocate the total electricity consumption as well as the packaging materials for the products of the company. The mass allocation procedure was selected on an annual production basis because it was not possible to find market prices for all the products.

Table 1 Global inventory for the ventilated wood wall under assessment

Inputs from technosphere			
Materials		Energy	
Oriented strand board (OSB)	36.0 kg	Electricity from grid	54.4 MJ
Medium density fibreboards (MDF)	21.0 kg		
Brazilian cedar sheets	22.3 kg		
Galician pine sheets	47.0 kg	Transport	
Gypsum-fibre sheet	36.0 kg	Truck	33.02 t·km
Anti-condensation sheet	0.31 kg	Van	7.75 t·km
Rock wool	3.78 kg	Transoceanic tanker	776 t·km
Copper salt	0.055 kg		
Ecological oil	0.78 kg		
Metal pieces	1.47 kg		
Corrugated board[a]	0.09 kg		
Pallet[a]	0.004 kg		
Plastic materials[a]	0.18 kg		
Diesel	0.75 l		
Outputs to technosphere			
Materials		Waste to treatment	
Ventilated wood wall	168.7 kg	Wood waste	80.0 kg
		Shaving	30.0 kg
		Sawdust	2.50 kg
		Plastics[a]	0.18 kg
		Pallets[a]	0.004 kg
		Cardboard[a]	0.09 kg
		Others	0.10 kg

[a]Packaging materials

Table 2 Summary of data sources

Electricity	Spanish electricity profile	Ecoinvent database (Dones et al. 2007)
Assembling	Oriented strand board (OSB)	Ecoinvent database (Werner et al. 2007)
	Medium density fibreboards (MDF)	Ecoinvent database (Werner et al. 2007)
	Wooden sheets (Brazilian cedar and Galician pine)	Ecoinvent database (Werner et al. 2007)
	Metal pieces (iron)	IDEMAT (2001)
	Plastic pieces (ethylvinylacetate foil)	Ecoinvent database (Hischier 2007)
	Fibres (rock wool, gypsum-fibre sheet and polyester resin)	Ecoinvent database (Althaus et al. 2007; Kellenberger et al. 2007)
	Chemicals (wood preservative)	Ecoinvent database (Werner et al. 2007)
Packaging	Corrugated cardboard	Ecoinvent database (Hischier 2007)
	Wood pallet	Ecoinvent database (Kellenberger et al. 2007)
	Plastic pieces (hoops and films)	Ecoinvent database (Hischier 2007)
Transport	Trucks, vans and transoceanic tankers	Ecoinvent database (Spielmann et al. 2007)
Maintenance	Ecological oil	Ecoinvent database (Althaus et al. 2007)

4 LCA study for the ventilated wooden wall

An LCA analysis for the production of the ventilated wooden wall was carried out according to the CML 2 baseline 2000 V2.1 biogenic method to quantify the environmental impact (Guinée et al. 2001). This method results in the definition of an environmental profile for the product under assessment by quantifying the environmental effects on ten categories, while only indirect or intermediate effects on humans can be assessed.

The impact categories analysed in this study were: abiotic depletion (AD), acidification (AC), eutrophication (EP), global warming (GW), ozone layer depletion (OD), photochemical oxidants formation (PO), and toxicological categories such as human toxicity (HT), fresh water aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME) and terrestrial ecotoxicity (TE). The LCA software SimaPro 7.10 developed by PRé Consultants (PRé Consultants 2011) was used for environmental impact assessment.

4.1 Characterisation results

Electricity requirements all over the production process could not be split up into the assembling and packing stages due to lack of information. It was only possible to compute the global electricity consumption. Therefore, the production of the electricity required was included in the environmental assessment as a separated stage due to its contribution to the environmental results. The results for the characterisation step are shown in Table 3.

Figure 3 shows the relative contributions of each of the four considered life cycle stages as well as electricity production in every impact category. According to these results, the assembling stage was the most important contributor to all the impact categories under assessment with percentages higher than 57% and even up to 87% for HT. The second most important contributor was the production of electricity (contribution up to 36% in categories such as AC and ME). The reason behind this contribution is that all the electricity is taken from the Spanish national grid which considerably depends on fossil fuels. Therefore, improvement alternatives should be focused on both stages.

4.1.1 Abiotic depletion potential

The assembling step was the main contributor with a percentage of 67% due to the board production and followed by the electricity production (25% of total). The main resources contributing to AD are oil, natural gas and uranium.

4.1.2 Acidification potential

Both the assembling stage and electricity production presented large contributions: 57% and 36%, respectively.

Table 3 Impact assessment results (characterisation step) of the ventilated wooden wall under assessment (169 kg of product; 2.40 m^2)

Impact category	Unit	Value
Abiotic depletion (AD)	kg Sb_{eq}	0.844
Acidification (AC)	kg SO_{2eq}	0.745
Eutrophication (EP)	kg $PO_4{}^{-3}{}_{eq}$	0.084
Global warming (GW)	kg CO_{2eq}	104.39
Ozone layer depletion (OD)	mg CFC-11_{eq}	9.33
Human toxicity (HT)	kg 1,4-DB_{eq}	63.91
Fresh water aquatic ecotoxicity (FE)	kg 1,4-DB_{eq}	7.08
Marine aquatic ecotoxicity (ME)	kg 1,4-DB_{eq}	1.32×10^4
Terrestrial ecotoxicity (TE)	kg 1,4-DB_{eq}	0.390
Photochemical oxidation (PO)	kg C_2H_{4eq}	0.042

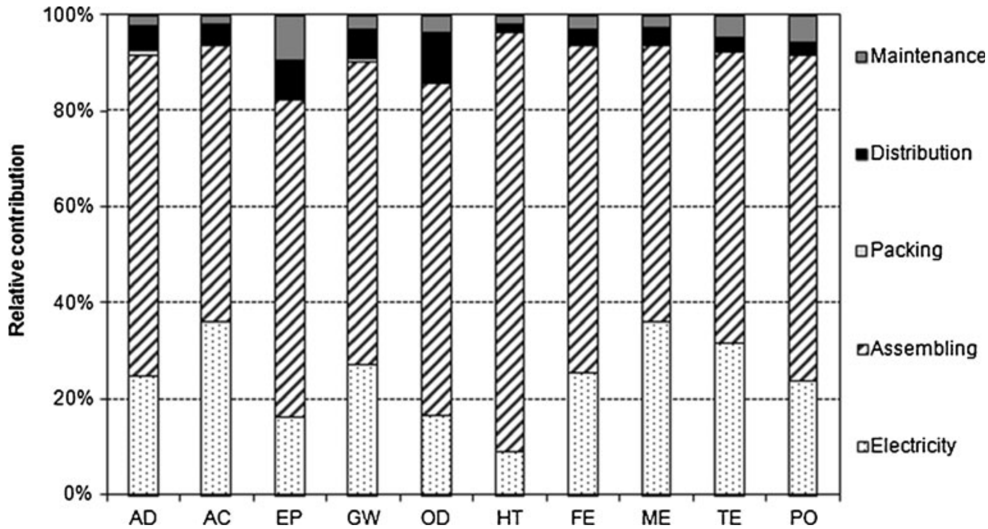


Fig. 3 Relative contributions per stages (in %) to each impact category. Impact category acronyms: *AD* Abiotic depletion, AC acidification, EP eutrophication, GW global warming, OD ozone layer depletion, HT human toxicity, FE freshwater aquatic ecotoxicity, ME marine aquatic ecotoxicity, TE terrestrial ecotoxicity and PO photo-oxidant formation

Emissions of SO_2 and NO_x are mainly responsible for this potential with percentages of 68% and 30%, respectively, of the total; these emissions are mainly derived from fossil fuel combustion.

4.1.3 Eutrophication potential

The assembling stage was responsible for 66% of the eutrophying emissions derived from the production and distribution of wooden materials. Concerning the contributing substances, airborne NO_x emissions showed the largest contribution to EP (~69% of total).

4.1.4 Global warming potential

The assembling stage was once again the mainly responsible contributor with a percentage of 63% followed by electricity production step (27%). Fossil CO_2 emission contributed to 93% of total GHG.

4.1.5 Ozone layer depletion potential

The contributions were also dominated by the assembling stage and electricity production (69% and 17%, respectively), mainly due to transport activities related with the distribution of raw materials inputs in the production process. Contributing substances to this impact category are Halon 1301 emissions (68% of total) derived from the processes involved in both stages.

4.1.6 Human toxicity potential

The assembling stage was once again the main hot spot with a contributing percentage of 87% of total due to airborne and benzene emissions, which represented 56% of the impact.

4.1.7 Ecotoxicity potentials

The assembling stage added up to 57%, 61% and 68% for ME, TE and FE, respectively, due to wooden board manufacture. Waterborne emissions, such as vanadium, barium and barite from fossil fuels combustion, dominate the substances which contribute to these categories.

4.1.8 Photochemical oxidants formation potential

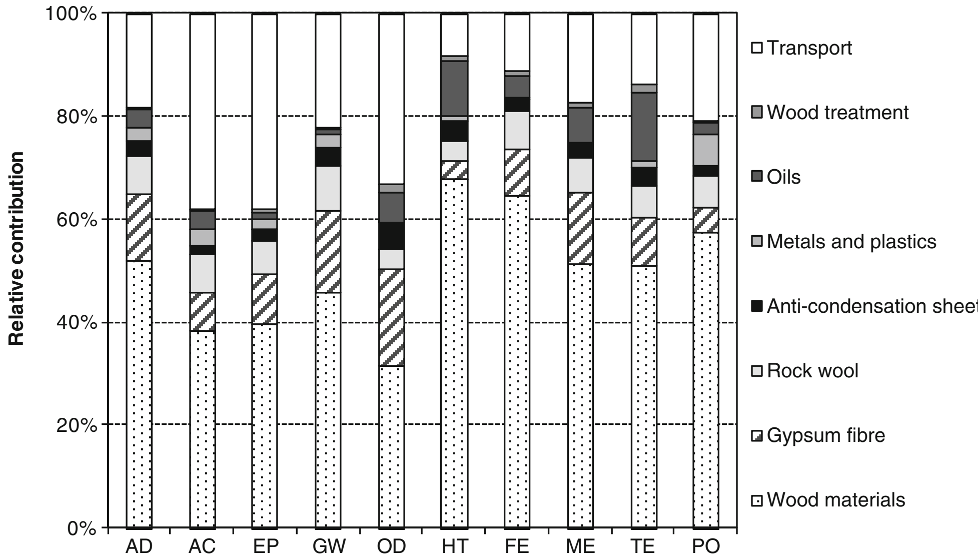
Once again the assembling stage was the mainly responsible contributor to this impact category (68% of total) mainly due to wooden materials production, followed by the electricity production (24%). Concerning the contributing substances, SO_2 is the main responsible substance with contributions of 48%.

4.2 Detailed assessment of the assembling stage

As it was described before, the assembling stage was the environmental key factor in all the impact categories under assessment. Therefore, this stage was analysed in more detail in order to identify the hot spots or the responsible processes of these environmental results. Figure 4 shows the relative contribution of the main processes involved in the assembling stage (excluding electricity production). This stage involves not only the material production (wooden materials, metals, plastics, fibres, etc.) but also their delivery, the wood treatment with cupper salts as well as the production of diesel and lubricating oils.

According to the results, the production of wooden materials was the main hot spot of the assembling stage due to the board production (OSB and MDF). It is important to note of the contribution of board production to toxicity-related categories (51–68%), PO (57%) and AD (52%). These results are related with the production of the phenolic

Fig. 4 Relative contributions per processes involved in assembling stage (in %) to each impact category. Impact category acronyms: *AD* Abiotic depletion, *AC* acidification, *EP* eutrophication, *GW* global warming, *OD* ozone layer depletion, *HT* human toxicity, *FE* freshwater aquatic ecotoxicity, *ME* marine aquatic ecotoxicity, *TE* terrestrial ecotoxicity and PO photo-oxidant formation



and urea formaldehyde resins used in the OSB and MDF production processes as well as due to the large requirement of electricity in their manufacture. Transport activities constitute another important environmental key factor in categories like AC and EP with contributions of 38% mainly due to the transport of the cedar by transoceanic ship from Brazil. Finally, gypsum-fibre sheet production used in the structure of the wall was the third key factor in the assembling stage with contributions of 16% and 19% in the GW and OD, respectively.

5 Design for environment study for the ventilated wooden wall

The LCA study identified the environmental key stages involved in the production process of the wooden wall. Therefore, the proposal of the eco-design strategies should consider their minimisation.

Table 4 shows the results from the eco-briefing. According to these results, the eco-design strategy should address changes on the concept definition and selection of the materials used. Concerning the concept, the targets are to reconsider the product functionality and to indicate technical solutions. With regard to the materials, the selection of the correct materials should be focused on supplies with lower environmental impact and optimized consumption.

5.1 Potential eco-design strategies

The eco-design strategies have to be evaluated from technical, economic and social points of view in order to integrate the three domains of sustainable development (González-García et al. 2011b). Only the potential strategies with higher viability to be implemented are the ones to be analysed and classified in quantitative and qualitative alternatives. It is important to remark that frequent interaction among the team members is essential to propose and analyse the potential strategies throughout the eco-design stage. LCA methodology can only be applied to the quantitative alternatives. Qualitative alternatives are the result of conceptual or formal improvement actions.

5.1.1 Quantitative alternatives

Alternative A: the reduction of the amount of both components and types of the materials used The use of wood-based materials was identified as a hot spot all over the life cycle of the ventilated wall due to the emission of potential toxic substances from the resins as well as high electricity requirements. According to the comments from the company experts, special attention has been paid on the total elimination of the MDF since its unique function in the structure is to hold the anticondensation sheet. Thus, the functional unit should be changed from 169 to 148 kg, and the contributions from production and distribution of the MDF should be excluded from the system boundaries.

Alternative B: the use of wood sheets with lower environmental impact associated It is important to remark the considerable contribution to the environmental profile of the cedar sheets from Brazil. Therefore, the proposed alternative has been focused on the substitution of Brazilian cedar sheets by another coniferous species from nearby zones with less associated transport. In particular, the use of red pine from Germany was considered. Therefore, this alternative is only focused on the transport distances assuming that there are no large differences in the coniferous cultivation.

Table 4 Definition of key environmental hot spots and life cycle stages for their solution

Environmental hot spots	Key life cycle stages to their solution					
	C	M	P	D	U	E
High amount of materials used in the production process	■	■	□	□	□	□
High diversity of materials	□	■	□	□	□	□
High amount of production stages	■	■	■	□	□	□
Low optimisation in product distribution	■	□	□	■	□	□
High maintenance level	■	■	□	□	■	■
	4	4	1	1	1	1

C Concept, *M* materials, *P* production, *D* distribution, *U* maintenance, *E* end of life

Alternative C: the use of renewable energy sources The use of electricity taken from the Spanish national grid is an important hot spot in the environmental profile. The production of electricity is mainly based on fossil fuels; therefore, the installation of solar panel on the roofs of the factory was proposed. According to this alternative, solar panels would produce 98% of the electricity annually required in the assembling and packing stages, which would imply that the plant would be electric energy self-sufficient.

Alternative D: the use of transport vehicles with lower environmental impact This alternative was proposed considering the distribution of final product to clients as well as the delivery of inputs for the manufacturing stage (González-García et al. 2011b). Therefore, the use of vans and trucks adapted to Euro 5 standards was suggested (EC Regulation No 715/2007 2007).

Alternative E: the use of biodiesel as transportation fuel Biodiesel was used as transportation fuel instead of diesel with substitution percentage of 20% (AFDC 2008).

5.1.2 Qualitative alternatives

Alternative F: definition of a protocol for the wood maintenance The maintenance protocol should be based on three issues: (a) basic maintenance (dust, leaves and other waste should regularly be cleaned in all the surfaces); (b) superficial maintenance (the surfaces should annually be brushed with water and air dried); and (c) wood treatment (use of ecological oils and/or water-based varnishes). The use of ecological oils and water-based varnishes could help to reduce the environmental impact associated to the product. In fact, it is recommended by the company to their clients. The combination of all of these issues should increase the durability of the wooden wall as well as could reduce the required oil/varnish dose.

Alternative G: definition of a protocol for the materials separation in their final management Up to date, the company has not taken into account the possibility of house dismantling because they consider that the reused components are limited and must be destined to a specific waste solicitor. However, it was proposed here due to the environmental improvements which could be achieved. An adequate dismantling protocol should allow increasing the possibility of recycling and reusing the components in the company as well as their potential energy valorisation.

5.2 Results of DfE from the quantitative alternatives

Characterisation results for each quantitative alternative under assessment can be found in the Electronic Supplementary Material since the discussion in this section was based on the normalized results. The normalisation phase allows us to compare all environmental impacts using the same scale as well as to add the normalisation values of the impact categories in order to obtain a single value per alternative. For this reason, we proposed to present the DfE normalized results of the quantitative alternatives. Figure 5 shows the normalisation index per alternative (A, B, C, D and E) as well as for the current product (X). These normalized indexes were calculated taking into account the normalisation values for the ten impact categories proposed by the CML methodology (Guinée et al. 2001). The situation in Western Europe has been taken as the reference for all the categories (data from year 1995) as this is the most complete list available (Guinée et al. 2001).

According to the normalisation results, the five alternatives led to a reduction in the environmental profile of the ventilated wooden wall. Alternative C shows the highest reduction (~45%) in the environmental impact due to the installation of solar panels, which substitute 98% of total electricity requirements by means of renewable electricity. This improvement alternative implies a remarkable economic investment which could be recouped in about 16 years. The intention of this paper was not carried out an economic analysis. However, the estimation of the repayment of the inversion due to the good environmental results achieved with the establishment of this alternative was considered. Supplementary material for the calculation is shown in Tables A1 and A2 in the Electronic Supplementary Material.

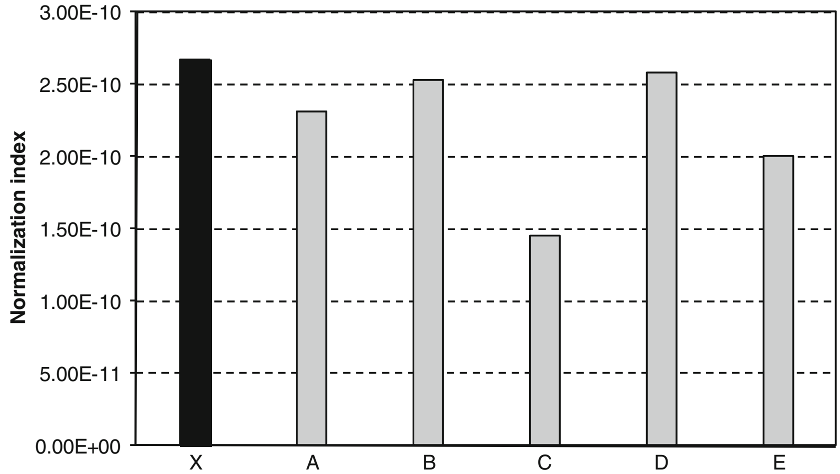


Fig. 5 Comparative profile between the current and alternative scenarios of the ventilated wooden wall in terms of normalisation index

The second most important reduction (~25%) was attained in the alternative E based on the use of biodiesel in transportation. The higher reductions are achieved in the EP (25%) and OD (23.8%) mainly due to the lower amounts of NO_x and Halon-1301 emissions, respectively. The other toxicity-related categories achieved significant reductions, up to 35%. The GWP was also successfully reduced by 13.8%.

The elimination of the MDF from the structure of the ventilated wall involves an environmental benefit not only by the production of the board but also by its corresponding transportation and lower weight of the final product (around 21 kg less). This board is only used as support for the anti-condensation sheet. If it is analysed in detail, the contributions to the toxicity categories can be reduced up to14% as well as to AD and AC mainly due to the reduction of the emissions related to electricity requirements associated to the MDF production process.

Concerning the remaining alternatives (B and D), it is possible to lightly improve the environmental impact (5.3% and 3.5%, respectively). Alternative B is based on the substitution of Brazilian cedar by German pine sheets, which involves a shorter transport. In this alternative, the same amount of sheets for the wall manufacture was considered, regardless of the raw material used and the forest operations. Therefore, the distinctive difference between both alternatives lies on the transport. The highest environmental reduction was achieved in AC (12.5%) due to the reduction in the NO_x and SO_x emissions. This reduction in the NO_x emission also involves a decrease in the EP (11%). With regard to the alternative D, the use of Euro 5 transport vehicles (vans and trucks) was proposed. The highest reduction was shown in the EP (14%) due to the reduction of the NO_x emission, which also contributes to reduce the contributions to AC by 7%. A similar reduction percentage was also achieved in OD due to the lower emission of Halon 1301.

We have not evaluated the qualitative alternatives from an environmental point of view (alternatives F and G) because they are based on changes on steps out of the system boundaries considered in this study. However, they could be interesting in a short–medium period of time for the company due to important environmental and economical benefits associated. The use of ecological oils and water-based varnish to treat the wood materials would help to reduce the environmental profile (alternative F). Ecological oils and varnish do not contain solvents, halogens and alcohols; they avoid the colonisation of fungi and bacteria as well as protect wood from the moisture and temperature changes. Concerning the proposal of a protocol for the materials separation in their final management, it could allow the reuse and recycling of materials to the production process, allowing the reduction of the corresponding materials production-related environmental burdens and production costs.

6 Conclusions

This work was focused on the analysis of the environmental profile of a ventilated wooden wall, an innovative structure for the wooden houses. The environmental key factors throughout the life cycle of the wooden wall were identified from the inventory analysis and the impact assessment results. Two complementary methodologies were taken into account in order to propose improvement alternatives: LCA and DfE.

According to the LCA study, two stages were identified as the main environmental impacts: the assembling stage (specifically, the production of boards and the transport of cedar sheets) and the electricity production stages with contributions around 66% and 25%, respectively, to all impact categories. Thereafter and according to the DfE, several improvement alternatives were proposed in the eco-design process specifically focused to minimize the contributions to the environmental profile from both stages.

Five quantitative alternatives (exclusion of the MDF from the wall structure, use of German red pine sheets,

installation of solar panels, use of Euro 5 transport vehicles and use of biodiesel in the transport) and two qualitative alternatives (definition of a wooden materials maintenance protocol and a material separation protocol in their final management) were proposed. According to the results, the installation of the solar panels on the factory roofs in order to produce the 98% of the total electricity consumption should be the best option with a reduction in the environmental normalisation index of 45% (reductions of 26% of global CO_{2eq} emissions and 15% of total energy consumption). The second highest reduction (25%) is achieved when biodiesel is used instead of diesel in the transport (reductions of 16% of global CO_{2eq} emissions and 6% of total energy consumption). All the alternatives proposed and evaluated are viable for the plant in a short–medium term from technological, economical and social perspectives.

Both LCA and DfE results for the ventilated wooden wall are complementary and their combination offers a qualitative and quantitative vision of the life cycle of the product under assessment. A correct methodological adaptation of the concept of eco-briefing, as a tool for communication among environmental technicians and designers, the simplification of the analytical tool used and the LCA facilitate the environmental analysis. The results obtained provide valuable information that can assist construction sector to improve their environmental performance and sustainability.

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